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Dynamic Priority based Reliable Real-Time Communications for Infrastructure-less Networks

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ABSTRACT The paper proposes a dynamic priority system at Medium Access Control (MAC) layer to schedule time sensitive and critical communications in infrastructure-less wireless networks. Two schemes, Priority Enabled MAC (PE-MAC) and Optimized PE-MAC (O-PEMAC) are proposed to ensure real-time and reliable data delivery in emergency and feedback systems. These schemes use a dynamic priority mechanism to offer improved network reliability and timely communication for critical nodes. Both schemes offer a notable improvement in comparison to the IEEE 802.15.4e Low Latency Deterministic Networks (LLDN). To ensure more predictable communication reliability, two reliability centric schemes Quality Ensured Scheme (QES) and Priority integrated QES (PQES) are also proposed. These schemes maintain a pre-specified successful packet delivery rate, hence improving overall network reliability and guaranteed channel access.

INDEX TERMS critical communications, industrial wireless sensor network (IWSN), Infrastructure less communications, MAC, machine to machine (m2m), priority, Quality of Service (QoS), ultra-reliable low latency communications (URLLC).

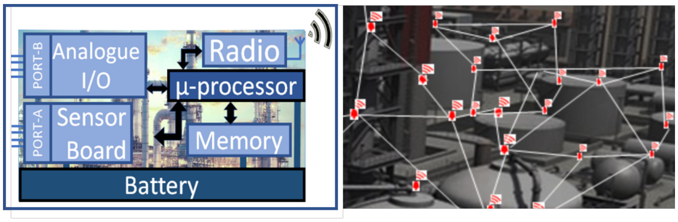
I. INTRODUCTION

OVER the years, radio communications technology has notably improved. The static communication systems have transformed into dynamic self-governing networks capable of anticipating and addressing network anomalies in real-time [1]. However, cellular wireless communication infrastructure primarily depends on Base Station Subsystems (BSS) which are responsible for ensuring communications of the affiliated devices and cellular phones. Under normal circumstances, the cellular and infrastructure-based systems work effectively. However, in special circumstances and in natural disasters, the wireless communications infrastructure can be severely incapacitated, hence affecting the communications of interconnected devices in exposed and vulnerable regions. In such cases, ad-hoc on-demand and peer to peer communications serve as an alternative to provide framework for structure-less communications [2]. Although wireless ad-hoc networks offer a suitable alternate to infrastructure-based communications under special circumstances, however, the added delays and reliability issues limit their scope. Therefore, suitable improvements are desirable to introduce robust communication schemes in the absence of communication infrastructure. Content based information selection for prioritized, time critical and reliability constrained communications are also desirable in such networks.

The investigation and developments of suitable strategies for infrastructure-less communications can assist in the context of disaster communications, machine to machine (m2m) communications, multi-purpose static and mobile networks, Internet of Things (IoT), smart networks and largescale sensor networks [3]. The communications in such networks can be classified based on their critical nature, where emergency communications, distress calls, control messages, wellbeing messages, alerting messages, data collection and irrelevant normal communications have different levels of priority [4]. Hence, a suitable mechanism is desirable to affiliate precedence levels to these messages and schedule them accordingly. In this paper, the design efforts are centred around the application of Industrial Wireless Sensor Networks (IWSNs), nonetheless, the proposed work potentially addresses reliability and latency issues in other infrastructure-less scenarios as well. IWSNs are formed of autonomous devices which sample and relay sensory feedback from various industrial processes. A distributed communications network is formulated to relay the information from sensor nodes to a control centre. These sensor nodes are usually equipped with microprocessors, radio, battery, sensor board and I/O interfaces, which allows heterogeneous sensing, localized processing and intelligent communications [3].

A graphical representation of wireless sensor nodes and a traditional IWSN is presented in Figure 1. Here, Figure 1 (a) presents block diagram of wireless sensor nodes whereas the sensor network is presented in Figure 1 (b). In comparison to traditional Wireless Sensors Networks (WSNs), IWSNs are a special domain of WSNs which particularly targets industrial applications [70], [71]. The working principles of both WSNs and IWSNs are similar, however, the strict timing deadlines, constrained reliability requirements and nature of industrial applications make IWSNs an entirely different research domain. In industrial applications, IWSNs may be required to monitor emergency processes, establish close loop control systems and perform time sensitive automation. Therefore, the primary research focuses in IWSNs are reliability, real-time data delivery and deterministic network designs. Due to the critical nature of industrial operations, network formation, topologies, information routing mechanisms, network architecture, and reliability requirements are accordingly designed. Under certain circumstances, IWSNs may also require a long network lifetime. However, the network lifetime requirements vary from application to application. Within the industrial environment, wireless sensor nodes are deployed in the vicinity of potentially valuable information sources. Depending on the nature of the sampled information, it can be used for both monitoring as well as feedback control systems and emergency systems.

Furthermore, the implementation of IWSNs in industrial environments offer notable cost reduction (less than €1 per meter wireless link compared to an upper limit of €4337 per meter wired link [4]) along with other features like self-organization, localized processing, ease of deployment and self-healing abilities. However, limited bandwidth, latency, reliability issues



(a) (b)

FIGURE 1: Industrial Wireless Sensor Networks

and battery-operated operations offer certain limitations which need to be addressed. Notable benefits of IWSNs over traditional wired networks have provided the much-anticipated research in this field. In the past decade, many industrial protocols surfaced, some of which include, Zigbee, WirelessHART, 6LoWPAN and ISA100.11a [3], [5]. Some of these protocols use IEEE 802.15.4 as a baseline for defining Physical and Medium Access Control (MAC) layer specifications. IEEE 802.15.4 uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [6] as the channel access method. Although the CSMA/CA based schemes have potential for low delay and high throughput, however, the guaranteed channel access is compromised. Moreover, the communication quality significantly degrades with the increase in the number of connected nodes. These attributes reduce the suitability of CSMA/CA based channel access control methods for most of the industrial applications. The industrial standards derived from IEEE 802.15.4 share same issues and hence are not suitable for emergency and critical applications with strict time deadlines [7], [8].

To optimize the performance of the IEEE 802.15.4 for industrial applications, IEEE 802.15.4e [9] was introduced. IEEE 802.15.4e primarily optimizes the channel access schemes by incorporating Time Division Multiple Access (TDMA). It ensures deterministic channel access. However, its suitability for low latency and time constrained networks is questionable. Furthermore, the standard and its variants (WirelessHART, ISA100.11a) use CSMA/CA based channel access scheme for retransmission of failed communications. Shared slots improve reliability, however, its CSMA/CA based access scheme and exponential back-off mechanism for channel unavailability (for details see [9]), serves as a probable cause for frequent violation of time constraints. Furthermore, a pre-specified Packet Reception Rate (PRR) for IWSNs cannot be ensured using IEEE 802.15.4e.

In industrial environments, interference in wireless communications is one of the major challenges. Interference is relatively high in industrial setup due to high noise, co-channel interference, humidity, dust, dynamic atmosphere, electromagnetic radiations and multipath distortion. These factors not only contribute to reduced range, distorted and noisy transmissions but also result in unreliable links,eventually leading to extended packet delays and high packet loss ratio. Therefore, to make the communication more reliable and to minimize channel congestion implementation of TDMA and improved channel access coordination is inevitable. Communication reliability is an important aspect in IWSNs and the underlying process control and system automation cannot work effectively without ensuring acceptable reliability levels. For critical applications involving emergency and regulatory control communications, 99.999% PRR is recommended to ensure effective working of underlying control algorithms. In industries, information from emergency systems, regulatory control systems, open-loop, supervisory systems and alerting and monitoring data can coexist and need to be provided appropriate priority levels for efficient scheduling [3]. Further to this, in feedback control systems, the sampled sensory data, depending on the criticality of its readings, also adds an urgency factor, which needs to be considered while scheduling such communications. Since in time critical applications, failure in communication or unwanted delay can have devastating effects. Therefore, it is important that IWSNs offer reliable communication platform for time critical applications without violating the hard deadlines. Like other critical networks, data traffic in industrial networks can be divided into multiple categories based on the critical nature of the information and can have heterogeneous time deadlines. This fact can be used to improve the performance of IWSNs by not only increasing the reliability of high priority information but also to ensure the timely delivery of critical data.

In this paper, a dynamic priority system is proposed to offer a real-time multi-level priority establishment to optimize emergency and critical communications. To improve the coexistence of traffic with different priorities, two priority enabled MAC schemes, PE-MAC and O-PEMAC are proposed. These schemes allow real-time and reliable communication of critical information within the emergency, regulatory and supervisory control systems. The schemes are further strengthened by incorporation of appropriate sleep scheduling to offer extended network lifetime. The paper also proposes two Quality of Service (QoS) centric protocols QES and PQES to offer guaranteed PRR within the network without violating the specified time deadlines of the communications. The main contributions of the work are listed as follows:

- A dynamic priority system is proposed based on three important aspects of industrial processes: i) the critical nature of the sensed data; ii) weight of the underlying process/control system depending on its importance; and iii) channel condition and deadline based information rescheduling.
- The use of dynamic priority system along with the proposed schemes PE-MAC and O-PEMAC allows rescheduling of failed (critical) communications within same superframe, i.e. within $10ms$ duration. This ensures the stability of underlying processes by avoiding destabilisation of the processes due to excessive delays (the limited delay ($< 10ms$) caused due to earlier failure in critical communications is handled with the inclusion of Smith predictors and other control systems prediction tools), enabling an overall prolonged system stability.
- The proposed schemes, PE-MAC and O-PEMAC, also facilitate a relatively higher communications reliability compared to IEEE 802.15.4e LLDN of critical data ensuring at least 99.999% PRR in O-PEMAC as recommended by International Society of Automation (ISA).
- To achieve desired QoS for diverse applications within the industries, two protocols QES and PQES are proposed with a predefined level of reliability to allow a pre-specified PRR for a set of applications. This allows easier customization of QoS, based on individual needs of various industrial applications.

Since the TDMA based channel access scheme is used with constant superframe duration, more effective sleep scheduling, replacement strategies and synchronization is guaranteed. A thorough evaluation of these schemes is also presented in this paper.

The rest of the paper is organized as follows: Section II presents Literature Review. System model is presented in Section III. Section IV discusses the results and presents performance analysis. Finally, Section V gives conclusion and future directives.

II. LITERATURE REVIEW

Recent developments in 5G and incorporation of Ultra Reliable and Low Latency Communications (URLLC) offers a platform to address the communication issues in time critical and emergency communications [10]. URLLC not only will introduce reliable means to interconnect people but also will allow connectivity of large number of smart devices for control and automation purposes [11]. URLLC is desirable in applications with stringent time and reliability requirements where it is expected to maintain stringent communication success probability and end to end delay [12]. The need for critical, time sensitive and emergency communications in infrastructure-less frameworks is evident. URLLC is much desired, whether it is post disaster rescue activities, highly sensitive process control, feedback systems or necessary machine to machine communications. MAC layer plays a prominent role in ensuring URLLC. MAC layer handles the access to the physical channel which includes generation of beacons, synchronization mechanism to the generated beacons, motes association and disassociation to personal area network (PAN), support for device security, handling guaranteed time slot mechanism and reliable link assurance between the MAC entities [6]. Therefore, some suitable changes in MAC can assist in the formation of appropriate solution for real-time and reliable communications.

Over the years, MAC protocols have significantly changed where the primary focus of the research steered from network lifetime extension to real-time and reliable communication, especially in IWSNs. The recent MAC protocols cannot target energy efficiency as the only design concern. Hence, more suitable schemes are needed which could establish balance in network lifetime and real-time reliable data delivery. MAC protocols, due to their larger number, are classified in several categories. Some of these classifications include: random, periodic, slotted, hybrid, asynchronous, synchronous, multi-channel, CSMA/CA, TDMA and priority enabled schemes [3], [13]. Each of these categories offers certain benefits. While some schemes are efficient for network lifetime enhancement (asynchronous, periodic, slotted), others offer improved reliability and data-rate (TDMA, multi-channel, hybrid). A limited account of priority enabled schemes is also introduced to offer real-time communications of critical data.

In IWSNs, the priority-based communication is yet to be fully explored and fewer schemes can be found that prioritize communication based on the source of the information. Some of the priority enabled MAC schemes can be found in [14]–[18]. In [14], an analytic approach was used to model the multichannel network. The authenticity of the model was established with simulation and numerical results. However, the scheme offers a static precedence system for prioritizing the communication. In [18], priority is established based on the information content in the messages. In this scheme, full duplex communication is used to meet the deadline requirements of the feedback control system. However, almost all of the commercially available nodes use half duplex communication [21], [22] which limits the scope of this scheme. In [17], authors present another priority enabled MAC scheme. The protocol divides the traffic of an industrial setup into four categories and high priority traffic is allowed to take over the low priority traffic bandwidth. However, it is a static scheme in which priorities once defined are not changed during the network lifetime. WirArb is defined in [15] which uses arbitration phase where each node uses preassigned arbitration frequency to find number of time slots it has to wait until its communication takes place. The protocol is evaluated using discrete time Markov chains and assures channel access for high priority users. However, this scheme also offers static priority as the arbitration frequency is preassigned, based on the priority of the node. Moreover, the scheme needs a special coordinator to receive all the arbitration frequencies and respond accordingly at once. The scheme also overlooks the need for number of orthogonal arbitration frequencies in case of large number of nodes. Further to this, the existing schemes are static in nature and are unsuitable for time constraint and critical applications. The existing schemes are mostly static in nature and offer certain limitations in time constraint and critical applications. Some of the schemes are also not tailored for industrial applications and overlook the requirements of industrial systems. Although the schemes proposed over time offer notable improvements, however, these schemes target different aspects of sensor networks. In comparison to these schemes, main contributions of the proposed work are highlighted in Table 1. This table lists one IEEE standard for industrial automation, four industrial protocols for monitoring and control applications, and nine articles published in 2013 to 2018 in IEEE transactions and other journals.

III. SYSTEM MODEL

Most industrial applications have a centralized control system where all functional blocks in the plant are connected to the control centre by IWSNs. However, with the dawn of new industrial age, distributed control processes are also introduced to offer robust response in critical feedback and emergency systems. Depending on the requirements and nature of the applications, the present IWSNs use both TDMA and CSMA/CA based channel access schemes. A suitable energy conservation mechanism is also utilised to offer extended network lifetime. Furthermore, in automation and process control, some emergency and control blocks are assigned a higher precedence compared to the rest. The information from these blocks need to be prioritized, whenever a shared wireless communication resource is used.

The proposed medium access protocol uses TDMA instead of the conventional CSMA/CA scheme to offer improved reliability and guaranteed channel access. The proposed scheme offers sleep scheduling for extended lifetime and a dynamic priority system to optimize information delivery to the control centre. Furthermore, the highly sensitive communications are suitably optimized to offer a certain reliability threshold for error free communication. A detailed description of the network topology, priority cost function, sleep scheduling, priority based time and reliability optimization and communication retransmission mechanisms is presented in the following sections.

A. NETWORK TOPOLOGY, SUPERFRAME STRUCTURE, DISTRIBUTION OF NODES AND SECURITY

In the proposed scheme, a star topology is considered with a support of data reception of twenty nodes in a 10-millisecond duration (specified feature of IEEE 802.15.4e, LLDNs [9]). The network scalability is ensured with the hierarchical architecture to meet with

TABLE 1: Comparison of proposed scheme with existing work

Attributes/ Contributions	**Proposed scheme**	**[9]**	**[27]**	**[28]**	**[29]**	**[30]**	**[17]**	**[15]**	**[31]**	**[32]**	**[33]**	**[34]**	**[35]**	**[36]**
Priority based communication	✓	N	✓	✓	N	N	✓	✓	✓	✓	✓	✓	N	✓
Real-time priority evaluation and incorporation for individual sensor nodes	✓	N	N	N	N	N	N	N	N	N	N	N	N	N
Incorporation of critical sensor reading for priority evaluation	✓	N	N	N	N	N	N	N	N	N	N	N	N	N
Guaranteed channel access assurance by eliminating opportunistic communications	✓	P	P	✓	N	N	✓	N	P	N	P	P	P	N
Synchronization optimization and inclusion of effective sleep scheduling	✓	N	✓	N	P	P	P	N	P	N	P	P	P	N
Rescheduling of critical failed communications within 10 ms duration to avoid control system destabilization	✓	N	N	N	N	N	N	N	N	N	N	N	N	N
Pre-specified QoS maintenance	✓	N	N	N	N	N	N	N	N	N	N	N	N	N
	✓: Covered				N: Not Covered					P: Partially Covered				

network growth demands. Since a TDMA based channel access scheme is used, nodes in the network are synchronized using a beacon signal at the start of each communication frame. The superframe duration is fixed to a period of 10 milliseconds to ensure low system latency which is suitable for time critical, industrial and emergency applications [9]. In addition, many applications in process control and feedback systems have a maximum sampling rate of 100 Hz (10 milliseconds) [3], [19]. It is therefore suitable for selecting the same duration for the superframe. The list of some of the common industrial applications and their update cycles are presented in Table 2.

The proposed superframe is presented in Figure 2 whereas the frequently used system variables are listed in Table 3. The superframe is started with a beacon followed by the communication of the individual nodes. A maximum of n nodes can communicate in a single superframe (n time slots per superframe). The initial k time-slots are reserved for High Priority Non-Replaceable Nodes (HPNNs). The next $m-k$ time slots are reserved for High Priority Replaceable Nodes (HPRNs). Rest of the time slots $(n-m)$ are for Low Priority Nodes (LPNs). The proposed scheme offers flexibility to alter the priority of HPRNs and LPNs in real-time to better suit the application requirements. Since n is the total number of nodes in a cluster, therefore in Figure 2, it is assumed to be twenty, i.e., the maximum number of nodes compensated in one superframe. For cluster sizes smaller than twenty, n will be less than twenty, as represented in Figure 3 (a), where n is less than twenty. Therefore, remaining time-slots are referred to as shared slots, used for retransmission of the previous erroneous data. Figure 3 (b) represents an individual time slot which is divided in s sub-slots each of duration s_d. Here each slot is divided in transmission section (Tx) and an acknowledgement section (Rx). Both transmission and reception (Tx and Rx) take place on different frequency channels in order to overcome time delays in switching from reception to transmission mode. It is to overcome the limitations of currently available wireless sensor motes, with half-duplex communications system. The two frequency channels used for communications (Tx and Rx) are separated by guard band of Ψ Hz.

Critical and emergency communications also face certain security threats. The security requirements are defined using the information type and consequences of tampering/obstructing the flow of information. Based on the critical nature of the information, the security requirements for different industrial applications are also presented in Table 2. The countermeasures to minimize the security threats include cryptographic key establishment, data encryption, key rotation, frame protection and device management. Within industrial environments, various industrial communication standards implement message integrity check, AES encryption, frame integrity check, entity authentication key etc., for added security features [3], [5]. In this work, stan-

TABLE 2: Typical end-to-end delay and update requirements for industrial processes [3], [19]

Applications	Update frequency	Security requirements	Battery lifetime
Monitoring and Supervision			
Vibration sensor [14], [19]	sec – days	Low	up to 3 years
Pressure sensor [14], [19]	1 sec	Low	up to 3 years
Temperature sensor [14], [19]	5 sec	Low	up to 3 years
Gas detection sensor [14], [19]	1 sec	Low	up to 3 years
Others/Data acquisition	> 100 ms	Low	up to 3 years
Maintenance diagnosis	Sec-days	Low	-
Close Loop Control			
Control valve [3], [14]	10 - 500 ms	medium to high	5 years
Pressure sensor [3], [14]	10 - 500 ms	medium to high	5 years
Temperature sensor [3], [14]	10 - 500 ms	medium to high	5 years
Flow sensor [3], [14]	10 - 500 ms	medium to high	5 years
Torque sensor [14], [19]	10 - 500 ms	medium to high	5 years
Variable speed drive [14]	10 - 500 ms	medium to high	5 years
Control Machine Tools [3], [14]	10 ms	High	up to 3 year
Interlocking and Control			
Proximity sensor [3], [14]	10 - 250 ms	medium to high	5 years
Motor [3], [14]	10 - 250 ms	medium to high	5 years
Valve [14], [19]	10 - 250 ms	medium to high	5 years
Protection relays [14], [19]	10 - 250 ms	medium to high	5 years
Machinery and tools	10ms	medium to high	up to 3 years
CAN bus Deadlines			
Periodic Messages [20]	5 - 20 ms	Medium	-
Non-periodic Messages [3], [20]	5 ms	Medium	-

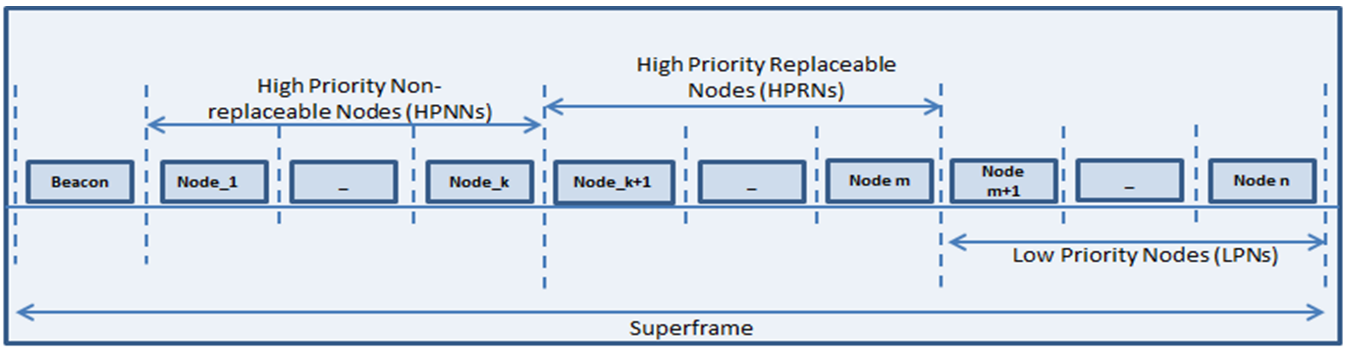


FIGURE 2: Superframe structure with n-Nodes

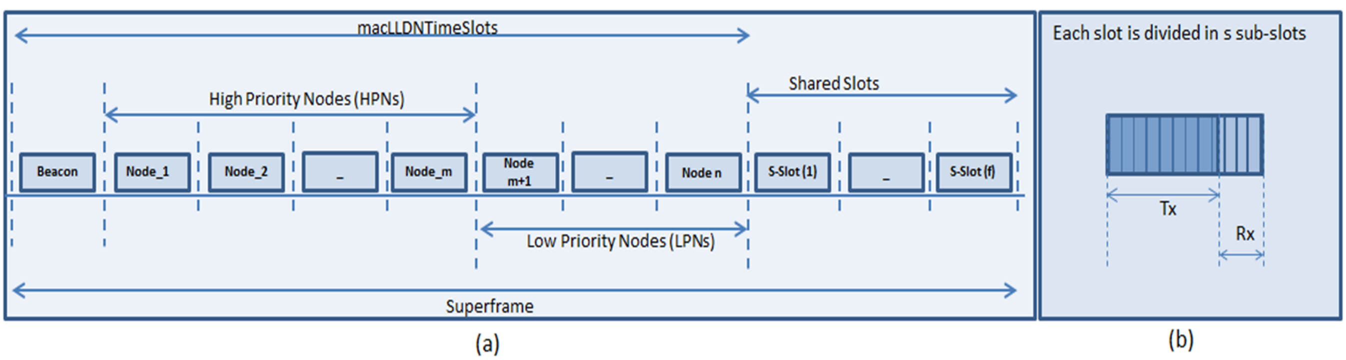


FIGURE 3: Superframe ($n < 20$)

TABLE 3: List of variables

Parameters	Variable(s)	Value(s)
Total Nodes per cluster	n	≤ 20
High Priority Nodes in a cluster (HPNs= HPNNs + HPRNs)	m	≤ 10
Low Priority Nodes (LPNs)	$n-m$	≥ 10
High Priority Non-replaceable Nodes (HPNNs) ∀ PE-MAC & O-PEMAC cases	k	$1 \leq k \leq 5$
High Priority Replaceable Nodes (HPRNs) ∀ PE-MAC & O-PEMAC cases	$m-k$	$0 \leq m-k \leq 9$
Probability of communication failure	q	$0 \leq q \leq 0.15$
Probability of communication success	p	$0.85 \leq q \leq 1$
Superframe duration	T_{sf}	$10ms$
Packet payload bits	$payload_bits$	960
Payload transmission time	PL_delay	$3.84ms$
No. of Subslots/timeslots per superframe (macLLDNnumTimeSlots)	s	20
Subslot duration	s_d	$\sim 300\mu s$
Guard band	Ψ	$5MHz$
Weight coefficients	$\alpha, \beta, \gamma, \delta_1, \delta_2$	$0.7, 0.15, 0.15, 0.6, 0.4$
Priority weight of node x	W_x	$0-3(normalizedto1)$
Critical information index of node x	CII_x	$0-1or0-100\%$
Sensor reading	r_s	
Weight index of node x	WI_x	$0-1$
Information failure index of node x	IFI_x	$0-1$
Probability of node replacement	p_n	$0-0.1$
Node replacement margin	υ	0.1
Wait time before the node timeslot replacement takes place	$wait\_state$	$2 \times T_{sf}$
Time required from communication initiation to delivery	δ_p	$300ns$
Percentage traffic delivered to destination	ω	$-$
Delay to deliver ω percent of the entire traffic generated by a high priority node	∂	$-$
No. of nodes scheduled for communication in a particular frame, ∀ QES & PQES cases	c	$-$
Desired QoS	D_Q	$99.9\% - 99.999\%$
No. of shared slots needed to achieve desired QoS	S_n	$-$
Percentage of priority nodes included in a cluster, ∀ QES & PQES cases	ψ	$-$

dard information security features are assumed for all communications however, as a future directive, adaptive security optimization can be introduced with application and information specific security attributes.

B. PRIORITY WEIGHT FUNCTION

Most of the existing priority enabled MAC protocols use a static priority system [15], [17] where a predefined precedence system, based on the source of information is established. Each node in the network is treated according to the predefined priority levels irrespective of the critical nature of the information. To compensate for the issues discussed above, a priority weight function is defined. The function takes following factors into account: i) communication in earlier time slots; ii) critical nature of the sampled data/information; iii) the natural precedence of the source of information; and iv) the consequence of failure in delivery. The priority weight function also allows the weighted contribution of all of the above stated factors. The priority weight function is defined as follows

$$W_x(t) = \alpha \times CII_x(t-1) + \beta \times WI_x + \gamma \times IFI_x(t) \quad (1)$$

where $W_x(t)$ is the Priority Weight of node 'x' at a particular time 't'. Based on this function, the precedence of nodes is defined in the network. In the proposed system, a higher value of $W_x(t)$ will lead to a higher priority. $CII_x(t-1)$ is Critical Information Index, defined on the basis of sensed values. If the received sensor values are within a stable range, $CII_x(t-1)$ will have a small magnitude but if the sensed values received at the cluster-head at time $t-1$ deviate from the stable range, i.e. violate the critical threshold, the magnitude of $CII_x(t-1)$ increases. $CII_x(t-1)$ is expressed as

$$CII_x(t-1) = \left[u(r_s-40) - u(r_s-60)\right] + \left[u(r_s-60) \times \frac{5}{2} \times (r_s-60)\right] + \left[u(40-r_s) \times \frac{5}{2} \times (40-r_s)\right]. \quad (2)$$

Here, 'r_s'is the normalized sensor reading (ranging from 0 to 100%):

$$r_s = f(sensed\ value) \mid \begin{cases} 40\% \leq r_s \leq 60\% & \text{stable range} \\ r_s < 40\% \| r_s > 60\% & \text{critical range} \end{cases} \quad (3)$$

The value of $CII_x(t-1)$ is also graphically presented in Figure 4. The figure represents value of a sensor over a period of time. In process control, the sensor value should be kept within certain thresholds, if the value exceeds the threshold, it becomes critical and requires immediate attention. In Figure 4, the green strip represents the stable/desirable range of sensor value. As long as the readings of sensor x are within the green strip, $CII_x(t)$ remains to minimum i.e. 1. As the sensor reading crosses the threshold value of $CII_x(t-1)$ starts increasing, as represented with the value next to the dotted points on the sensor value plot in the figure. Higher the value, more critical the sensor reading and more priority will be provided to this information.

As represented in the Figure 4, the sensor value is normalized between 0-100% where the mean values i.e. 40%-60%, represent stable range. If the sensor value deviate from the mean values it becomes more critical and farther the value is from the mean value more critical it becomes. The change in the color shades from green to yellow to red indicate the increase in the critical level of sensor reading where green is the least critical, while red is the most critical. WI_x is a time independent parameter based on value and importance of the equipment to which a node x is attached. To maintain linearity in scale, WI_x is adjusted between 0 and 100% with 100 being most significant sensor value and zero being the least significant sensor value. Technically WI_x of node x can have any value between 0% - 100% however, for evaluation purposes, six values 0, 20 , 40, 60, 80 and 100 have been used. $IFI_x(t)$ is defined on the basis of predicted consequences of not delivering/delaying information to central unit from source 'x' at time 't'. Its value depends of channel conditions, failure in earlier communication attempts and time deadlines. $IFI_x(t)$ is defined as

$$IFI_x(t) = \left[\left(\frac{1}{T_{deadline} - t}\right) \times \delta_1\right] + \left[\frac{1}{q} \times \delta_2\right] \quad (4)$$

Here, $T_{deadline}$ is the specified time deadline for an information to be delivered from source node to the cluster head. The packet delivery failure ratio, $(1/q)$, is used to ensure sufficient time for retransmission of packet. If the packet delivery failure ratio of a node exceeds certain threshold, the node is flagged at the coordinator. The added functionality allows the protocols to flag the nodes with high failure rate within the network to limit the excessive access to the available resources. δ_1 and δ_2 specify contribution of both time deadline and channel conditions. Note that all of these parameters are dealt as the attributes of the node object, which are uniquely identifiable at every node.

The graphical representation of change in weight value of individual components of $IFI_x(t)$ over time is represented in Figure 5. In figure the value of components of $IFI_x(t)$ is evaluated for two nodes. One of the nodes (Node1) form an integral part of low latency

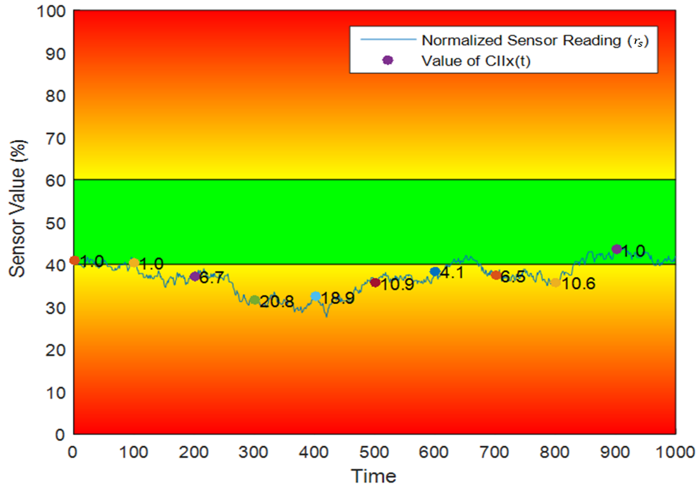


FIGURE 4: Normalized sensor reading 'r_s' along with the calculated Critical Information Index (CII) for a selected node

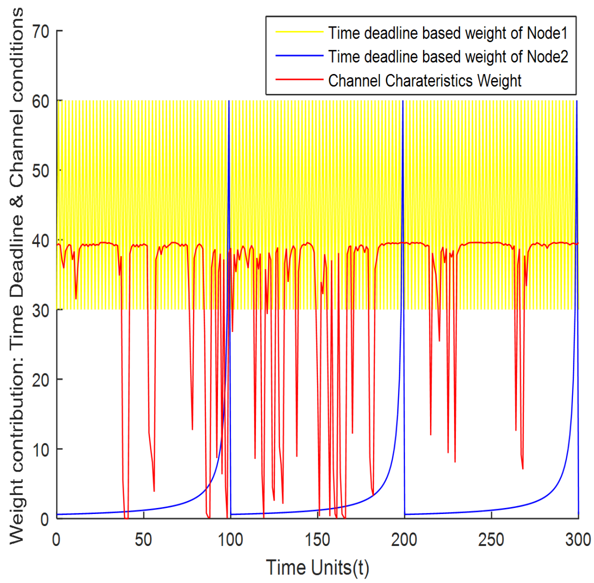


FIGURE 5: Information Failure Index $(IFI_x(t))$ components

process control loop and hence need to communicate the readings every 20 milliseconds. Second Node (Node2) is used for monitoring applications and is mandated for one communication every second. The changes in Packet Reception Rate (PRR) for Node2, over the period of time is also presented in Figure 5 whereas the accumulated value $IFI_x(t)$ is presented in Figure 6.

The parameters α, β and γ are introduced as the weight contributions. In other words, they incorporate flexibility and ensure weighted ensemble in priority weight function. Selection of the range of α, β and γ are dependent on applications. Some selected cases with certain conditions on α, β and γ are presented as follows:

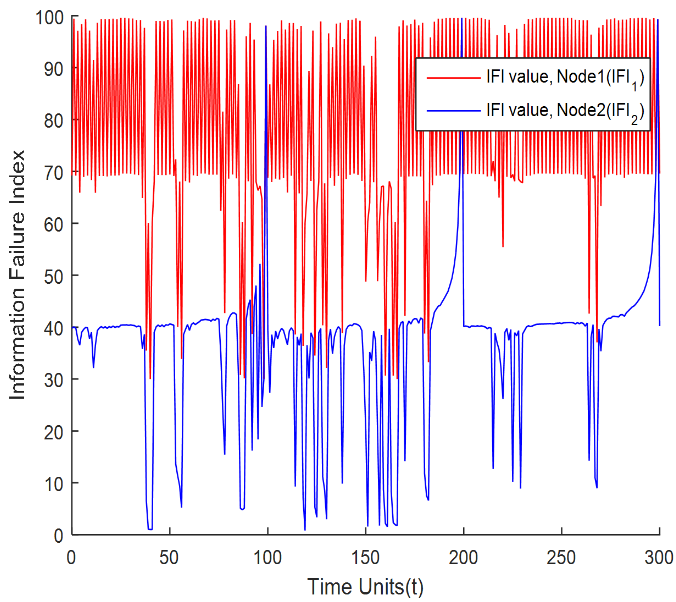


FIGURE 6: Changes in accumulated value of $IFI_x(t)$ over time for selected nodes

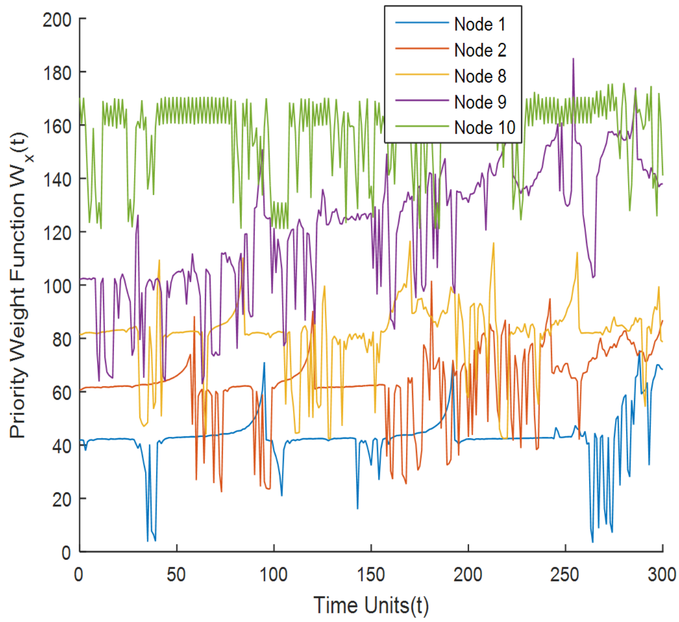


FIGURE 7: Priority weight function (W_x) values of selected nodes over time

- To ensure the weighted sum of all the parameters, $CII_x(t-1), WI_x$ and $IFI_x(t)$, α, β and γ must have comparable magnitudes.
- To ensure static priority hierarchy, primarily based on the value and importance of the equipment, $\beta \gg (\alpha \& \gamma)$
- To ensure less frequent shift in the priority of nodes and to guarantee that the priority of nodes only change in critical cases, ranges of α, β and γ should be adjusted so that $(\beta > \alpha)$ & $(\beta > \gamma)$. For such cases, change in $CII_x(t-1)$ and $IFI_x(t)$ will not have significant effect on the priority weight of the nodes, except where the critical thresholds are violated, hence very occasionally the priority of HPNs is reduced to give precedence to other critical nodes.
- To ensure uniform contribution from each parameter in the priority weight function, $\alpha \approx \beta \approx \gamma$
- To ensure the timely delivery of the critical data to the cluster head α, β and γ should be adjusted so that $(\alpha > \beta)$ & $(\alpha > \gamma)$. To suppress the subsequent failures in the transmission of individual nodes α, β and γ should be adjusted such that $(\alpha > \beta)$ & $(\gamma > \alpha)$. The stated configuration allows the node's priority to rise instantly with the failure in its communication.

Note that α, β and γ are used to incorporate weighted sum of key parameters in priority weight function. The optimal values of α, β and γ will vary depending on application at hand and significance of each of the considered parameters. The weight coefficients are being discussed in further detail in Table 4. In this table, selected cases are discussed where the suitability of certain coefficient values in weight function is mapped to six classes of process automation and control systems, namely, emergency systems, regulatory control systems, supervisory control systems, open loop control systems, alerting systems and monitoring systems.
A representation of changes in the priority weight function value ($W_x(t)$) over time for selected nodes (with $\alpha \simeq \beta \simeq \gamma$) is presented in Figure 7 whereas the priority levels (higher the value higher the priority) of selected nodes is presented in Figure 8. As the *wait_state* is $2 \times T_{sf}$ therefore, the priority levels are not instantly changed. If the *wait_state* is reduced to T_{sf}, priority levels will change exactly with priority weight function values. Further details in this regard are presented in Section III-C and Figure 9.

C. NODES' TIMESLOT REPLACEMENT

With the dynamic priority system in place, it is necessary to incorporate schemes which can benefit from the priority system and can result in overall improvement in reliability and real-time data delivery in the industrial wireless networks.

To support reliable communication of high priority nodes within a single superframe duration, the HPNs are scheduled at the start of the superframe. This arrangement ensures retransmission within the specified deadline. As represented in Figure 2, the first k time slots are reserved for high priority nodes and are non-replaceable. However, one or more HPRNs can be demoted to LPNs if their priority level decreases due to the

TABLE 4: Weight coefficients for ensemble priority weight function (selected values)

α	β	γ	**Conditions/ Comments**	**Ensemble Priority Cost Function Status**
α	β	γ	Dynamic P priority systems where α, β and γ are comparable	Weighted, suitable for regulatory control systems with various applications sharing same geographical space
1	0	0	Only critical information index is considered. i.e. Priority of the packet is solely defined on the basis sensor reading	Suggested combination is suitable for emergency and supervisory control systems where information is reported whenever certain threshold is crossed
0	1	0	Predefined, static priority	Provides a predefined priority for mostly static industrial environments with clear separation in control systems and monitoring applications
0	0	1	Deadline based scheduling	Priority function with these attributes can be used as a deadline-based scheduler
1	1	1	All the factors in priority value contribute equally	Balanced: retransmission decisions are based on the critical nature of sensory data, deadline, importance of the underlying process control in the industrial environment and probability of failure in communication
1	0	1	Dynamic priority suitable for single class of processes	Provides dynamic priority for single class of process control applications, whether it is regulatory control, supervisory control systems, open loop control systems or alerting systems.
α	β	γ	$\beta > \alpha$ & $\beta > \gamma$; Change in CII and IFI will not have significant effect on the cost of such nodes, hence very occasionally their priority level is reduced to give precedence to other critical nodes.	For cases with high priority non-replaceable nodes. Suitable when Emergency systems use same channel for communications as regulatory control systems.

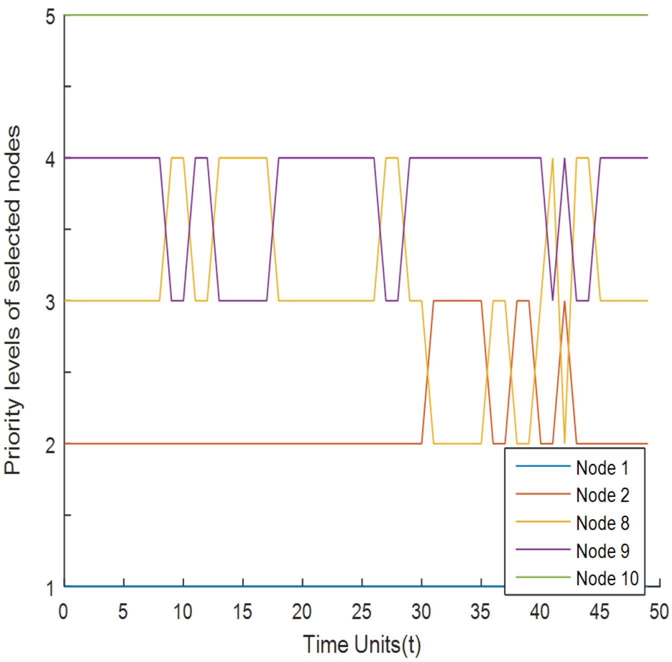


FIGURE 8: Priority levels of selected nodes over time

stable information feedbacks in previous time slots from these nodes. Such a change can be triggered by an event where the priority value of LPNs exceeds the priority level of HPRNs by a specified margin (υ). In such cases, the associated time slots of the nodes must also be switched. The replacement of node's transmission slot can be achieved with a rescheduling instruction from the coordinator. However, to ensure an error free transition, the slot swapping takes place after certain predefined wait states. The process of swapping HPRNs with LPNs is depicted in the flow chart presented in Figure 9.

After the completion of each superframe, the coordinator evaluates and compares the priority index of all the HPRNs and LPNs. If the priority index of a LPN is less than the priority index of a HPRN, nothing is changed and previously allocated slot sequences are used. However, if the priority index of one or more of the LPNs is greater than that of the HPRNs and fulfils the minimum specified margin requirements, υ, a change sequence is initiated. To filter out misread spikes in the priority index of the nodes, a certain waiting time ($wait\_state$) is introduced to postpone the change by pre-specified time units. It also ensures the error free shifting of nodes from one slot to another. If the initiated replacement remains valid for the time duration equal to $wait\_state$, the swapping would finally take place. It is noted that the replacement of the nodes during the network lifetime is also dependent on the number of HPRNs $(m-k)$ and number of LPNs $(n-m)$. Hence, in the worst scenario, the total number of nodes replaced in a unit time can reach up to the number of LPNs $(n-m)$ or number of HPRNs $(m-k)$, depending on whichever is smaller.

A generalized relation for the probability of number of replacements in a single time unit in either cases $n-m > m-k$ or $m-k > n-m$, i.e., HPRNs>LPNs or LPNs>HPRNs, is represented as

$$P_R(r) = \binom{x}{r} p_n^r \left(1-p_n\right)^{x-r} \quad r = 1,2,3,...min\left[(m-k)\right., \left.(n-m)\right]. \tag{5}$$

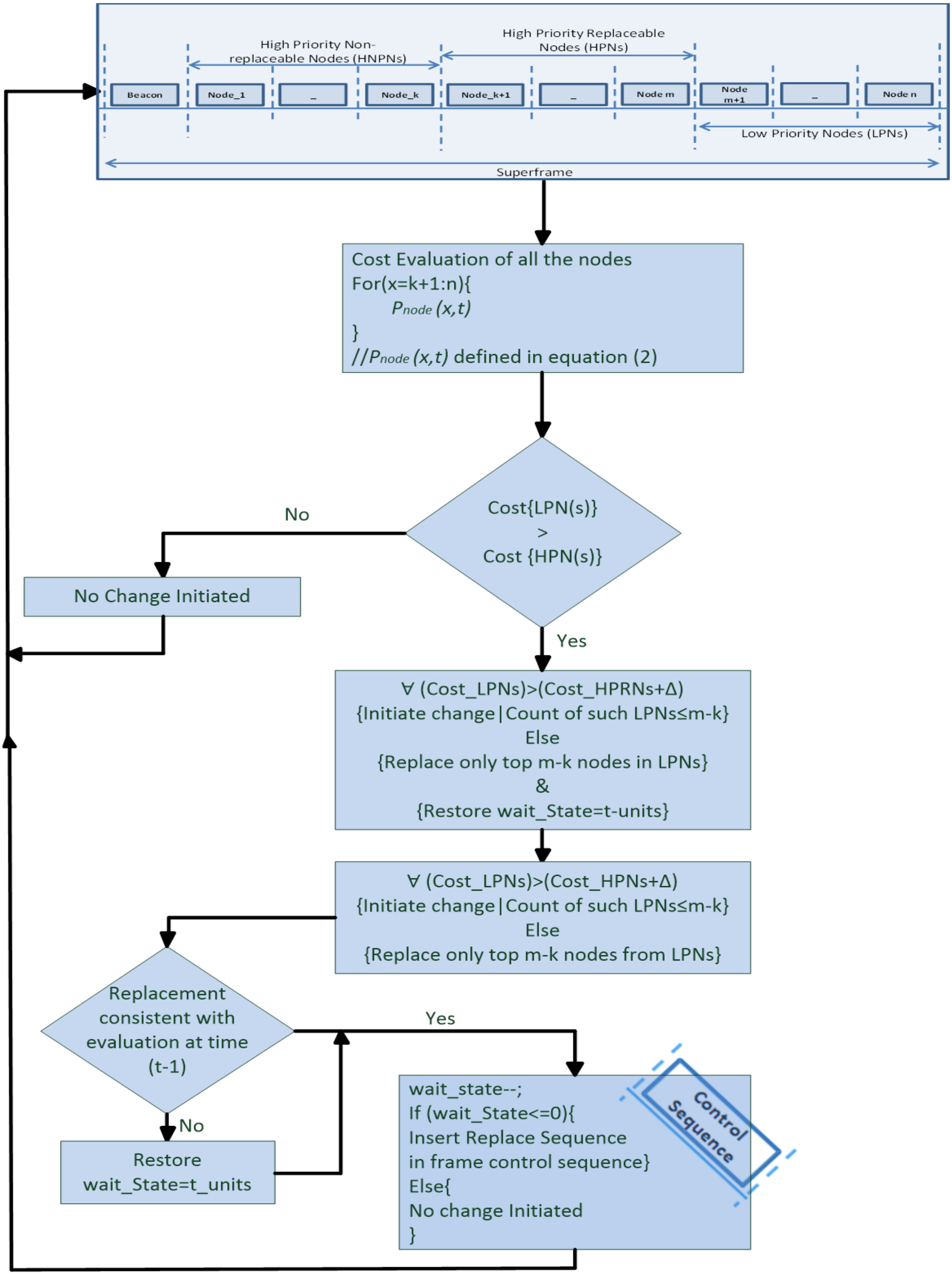


FIGURE 9: Priority based node scheduling and replacement mechanism

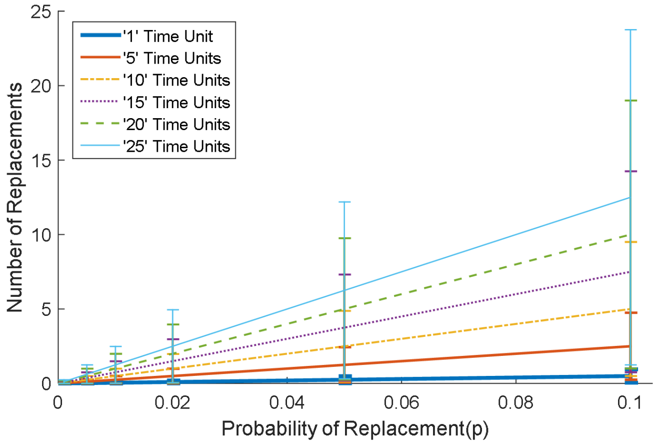


FIGURE 10: Average replacements and the expected deviation over time

Here, p_n is the probability of replacement of a single node and can be expressed as a function of priority weight function ($W_x(t)$), probability of communication failure, mean and variance of the sensed values, specified critical thresholds of the sampled information and stable data range boundaries. In the presented case, '1' time unit specifies the time duration of a superframe. Since the superframe duration can change, therefore, time units are used instead of more conventional time scales, milliseconds, seconds or minutes.

As represented in Figure 2, the HPRNs occupy dedicated slots in the superframe, and out of the $n-k$ nodes (all replaceable nodes in the network) only most critical nodes can be allocated these slots. Since a dynamic priority system is used, an LPN can become an HPN based on parameters defined in Eq. 1. With the change in the priority of nodes, the allocated time slots in the superframe are also changed. In order to ensure error free execution of the protocol, these replacements must be kept to a minimum. Timeslot replacement can be set to a minimum with an efficient priority weight function. For experimentation purposes, HPRNs are limited to a maximum of five, however, the scheme can easily be extended to higher number of HPRNs. Based on the mathematical modelling, the replacement patterns are presented in Figure 10. In the figure, average replacement as well as possible deviations from the mean are presented. It can also be seen that the replacement requests increase notably as the status of the nodes start changing more quickly. Therefore, to maintain a steady network, it is suggested to limit the replacement probability of timeslots to 0.05 or less.

D. SLEEP SCHEDULING AND PRIORITY BASED CHANNEL ASSIGNMENT

In the time critical industrial applications, the energy conservation is not always a major concern, however, an extended network lifetime is always desirable. To achieve a prolonged network lifetime in the proposed scheme, a sleep schedule is defined. An effort has been made to efficiently trigger nodes among active and sleep states to conserve as much power as possible without undermining the network performance. In Figure 11, a sleep scheduling algorithm is presented. In the figure, it can be seen that the HPNs (Node 1 to Node m) are only active when the actual communication is taking place. However, LPNs (Node m+1 to Node n) are active, either when they are communicating or when the high priority node, they are affiliated to, is communicating with the cluster head. For instance, during the transmission slot of Node 1 (S_{node_1}), LPN, node $m+1$, is also active, so in case the communication from Node 1 fails, its slot can be reserved for the retransmission of Node 1 data. In such cases, LPNs need to be active only during the period represented by yellow stripe (see ① in Figure 11) in order to receive the broadcast from the coordinator (cluster head) regarding status of the communication by the relevant HPN. However, due to the short duration of this period, currently available radio modules [23]–[26] are incapable of switching between active and sleep states so suddenly, hence, the active duration is taken equal to one complete time slot.
To facilitate the retransmission of HPNs, the LPN slot is reserved when communication fails. The scenario is presented in Figure 11. When the communication from Node 3 is failed and as a response, the time slot of the LPN e.g. Node $m+3$ is reserved (see ② and ③). Similar case can be seen in ④ and ⑤ in Figure 11. Therefore, during the slots S_{node_m+3} and S_{node_m+1} (dedicated slots of LPNs, reserved for retransmission of data of HPNs) the retransmission from HPNs, Node 3 and Node m, takes place (see ⑥ Figure 11), whereas the LPN Node $m+1$ and Node $m+3$ remain in the sleep state (see ⑦ Figure 11). A graphical demonstration of a superframe execution and priority based channel allocation is represented in Figure 12. In the depicted schedule in Figure 11, a special case is considered where HPNs are more than the low priority nodes, so a second iteration is run in which the time slots of LPNs not yet reserved are affiliated to the remaining HPNs in a cyclic manner as represented by the arrows (see ⑧ Figure 11).

E. MATHEMATICAL MODELLING

In context of the above discussion, the communication optimization of HPNs is ensured with two protocols, Priority Enabled MAC (PE-MAC) and Optimized Priority Enabled MAC (O-PEMAC). Both schemes target efficient scheduling of communications for HPNs and optimized retransmissions of to meet critical time deadlines and to ensure acceptable reliability. PEMAC allows single retransmission of a failed communication originated from a HPN, given a slot for LPN is available. In O-PEMAC, multiple retransmissions can be allowed

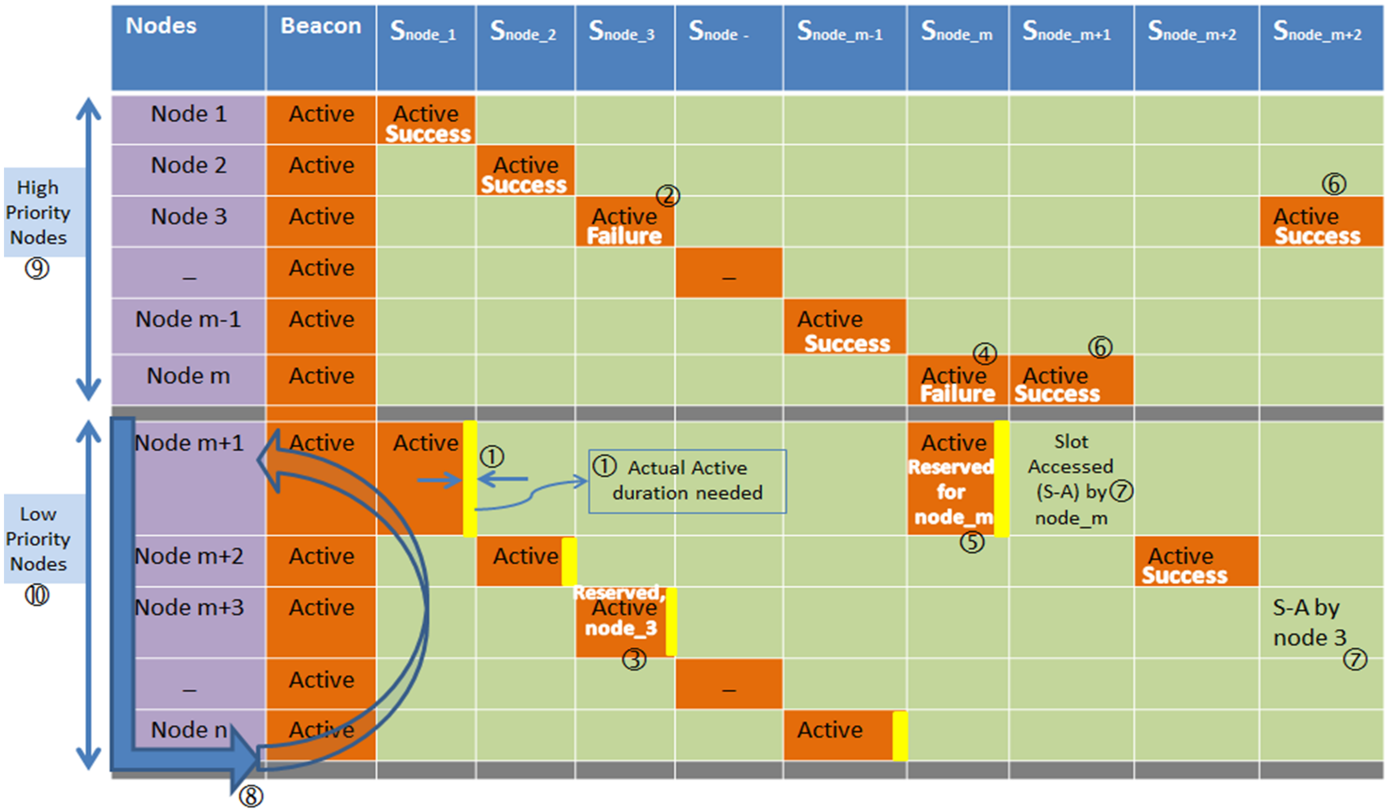


FIGURE 11: Sleep scheduling and priority based channel allocation

to ensure the delivery of information from HPNs to the coordinator within the specified deadline. To offer deterministic reliability, two more protocols, Quality Ensured Scheme (QES) and Priority integrated QES (PQES) are also proposed in the following discussion. To maintain pre-defined communications reliability in QES, the ratio of transmission slots to shared slots is established to achieve desired PRR. Whereas, a hybrid scheme is proposed in PQES which takes into consideration both priority weight function and QES to offer selective improvements in the communication of the critical nodes in IWSNs.

In order to quantify the overall improvements of the proposed schemes, a mathematical formulation of the possible scenarios for IEEE 802.15.4e LLDN [9] as well as the proposed schemes is presented. Due to the similarity of the problem with binomial distribution, the probability of failures in communication of nodes in any particular superframe is modelled as a binomial distribution. The probability mass function of Binomial(u, z) is presented in Eq. 6:

$$P_V\left(v\right) = \binom{u}{v} z^v \left(1 - z\right)^{u-v}. \tag{6}$$

Here, u is the number of independent trials, each with success probability z. In the proposed scenario, independent trials refer to the communication attempts from different sensor nodes distributed across the sensing field. Due to different geographical location, distance from the coordinator and different communication times, these communications are considered independent. In the proposed scenario, a clustered star topology based IWSN is used in which two consecutive transmissions from an individual sensor node are separated by a notable time gap, making two transmissions uncorrelated.

1) Percentage Error/Failure percentage in Communication of HPNs in IWSNs using IEEE 802.15.4e LLDN framework

In any single hop network, the communications failure primarily depends on the channel conditions and can be influenced by multiple factors including multipath fading, dispersion, reflection, refraction, interference, distance, congestion, transmission power restrictions and receiver sensitivity. In this case, since the error in communications of HPNs is evaluated over an entire frame, therefore, higher number of HPNs results in higher probability of error. With the increase in the number of HPNs, the possibility of at least one failed transmission from these HPNs increases significantly. To model the failure in communication, binomial distribution is considered where the total number of HPNs is represented by m. The probability of failure (q) in a single communication between source and coordinator is assumed to be symmetrical and independent of the earlier transmissions. For $\mathcal{F}_L$ be the event of

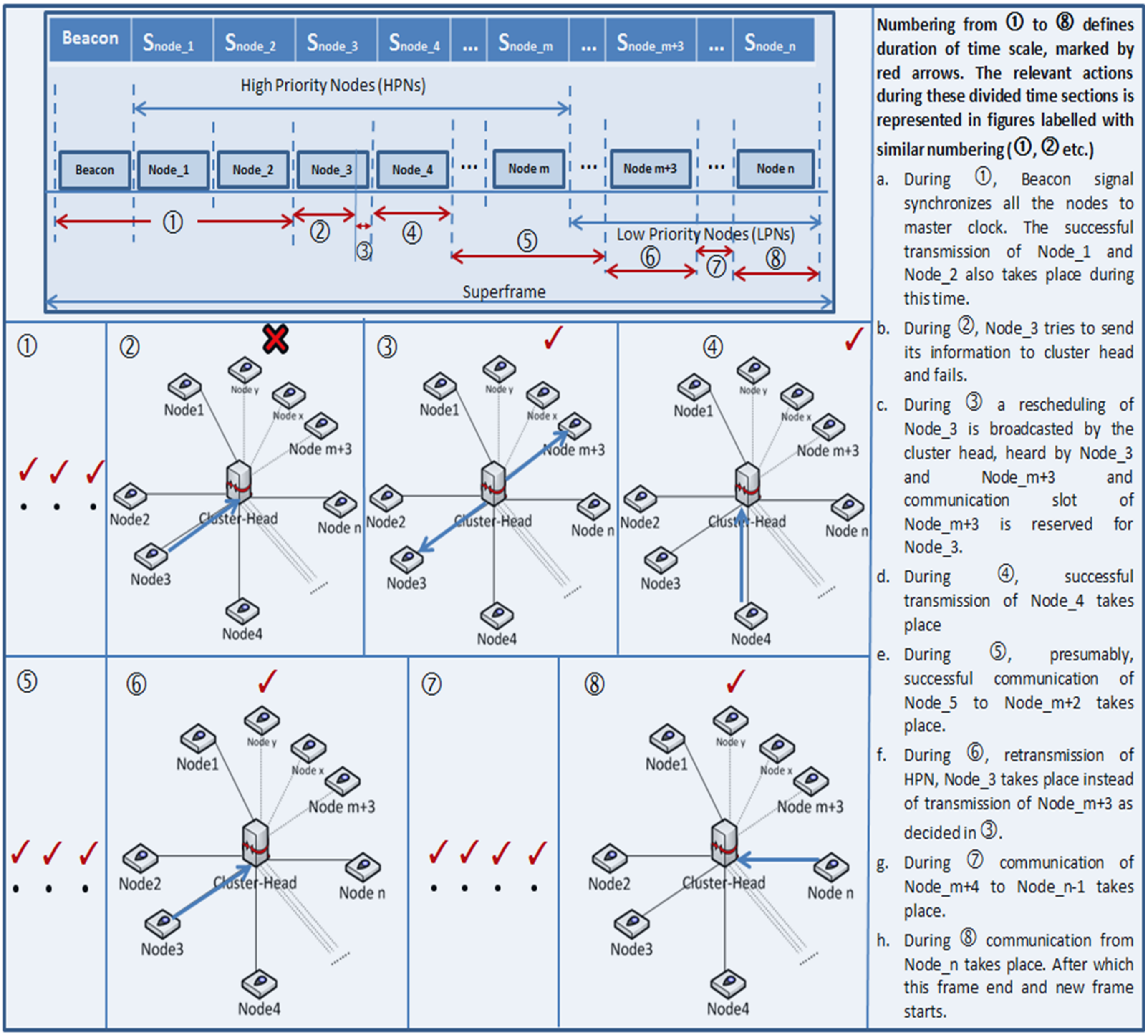


FIGURE 12: Demonstration of the superframe execution and the priority based channel allocation

HPNs communication failure in IEEE 802.15.4e LLDN scheme, The probability of at least one failure in HPNs communication, $P(\mathcal{F}_L)$, is represented in Eq. (7):

$$P\left(\mathcal{F}_L\right) = \frac{m!}{1!\left(m-1\right)!}q\left(1-q\right)^{m-1} + \frac{m!}{2!\left(m-2\right)!}q^2\left(1-q\right)^{m-2} \times \\ + ... + \frac{m!}{m!\left(m-m\right)!}q^m\left(1-q\right)^{m-m} + \sum_{x=1}^{m}\binom{m}{x}q^x\left(1-q\right)^{m-x} \tag{7}$$

2) Percentage Error/Failure in HPNs' Communication in PE-MAC and O-PEMAC

To enhance the performance of proposed scheme, the number of LPNs affiliated to a single coordinator should be greater than or at least equal to the number of HPNs. The above stated condition limits the number of HPNs in low latency networks to a maximum of ten. One must consider this as a soft bound to reap full potential of the proposed scheme. Nevertheless, in order to evaluate performance for both the cases, a system of equations is developed. Each of these cases is listed as follows.

a: Case 1: (n-m>m, i.e. LPNs > HPNs)

In the proposed scheme PE-MAC; given that the LPNs are greater than HPNs and $\mathcal{F}_P$ be the event of HPNs communication failure in PE-MAC, the probability of failure in HPNs communications,$P(\mathcal{F}_P|(n-m)>m)$, is represented in Eq. (8):

$$\begin{aligned} P\left(\mathcal{F}_P|(n-m)>m\right) = {} & \frac{m!}{1!\,(m-1)!}q\left(1-q\right)^{m-1}(q) + \frac{m!}{2!\,(m-2)!}q^2\left(1-q\right)^{m-2} \times \left[\sum_{x=1}^{2}\binom{2}{x}q^x\left(1-q\right)^{2-x}\right] \\ & + \ldots + \frac{m!}{(m)!\,(m-(m))!} \times q^m\left(1-q\right)^{m-(m)} \times \left[\sum_{x=1}^{m}\binom{m}{x}q^x(1-q)^{m-x}\right] \end{aligned} \tag{8}$$

In this case a single retransmission of failed communication from HPNs is allowed. The retransmission takes the dedicated slots of LPNs. In O-PEMAC, the retransmission of one or more failed HPNs communication is carefully scheduled with ability to retransmit multiple times given the network conditions are fulfilled. For $\mathcal{F}_O$ be the event of HPNs communication failure in O-PEMAC, the failure in communication of HPNs,$P(\mathcal{F}_O|(n-m)>m)$, is expressed in Eq. 9:

$$\begin{aligned} P\left(\mathcal{F}_O|(n-m)>m\right) = {} & \frac{m!}{1!\,(m-1)!}q\left(1-q\right)^{m-1}(q)^{n-m} + \frac{m!}{2!\,(m-2)!}q^2\left(1-q\right)^{m-2} \times \\ & \left[\sum_{x=n-m-1}^{n-m}\binom{n-m}{x}q^x\left(1-q\right)^{n-m-x}\right] + \ldots + \frac{m!}{(m)!\,(m-(m))!}q^m\left(1-q\right)^{m-(m)} \times \\ & \left[\sum_{x=n-m-(m-1)}^{n-m}\binom{n-m}{x}q^x(1-q)^{n-m-x}\right] \end{aligned} \tag{9}$$

In this case, the performance of communication in HPNs is improved by allowing multiple retransmissions. While the proposed O-PEMAC offers enhanced optimization in HPN, it also affects the communication efficiency of the LPNs up to some extent. Therefore, to improve the communications efficiency of LPNs, heterogeneous sensing is introduced to minimize communications failure in LPNs by affiliating variable time deadlines. The variable time deadlines along with the information of $IFI_x(t)$ (failure in earlier communication slots of node x) is used to define whether the LPN 'x' should be reserved for communication of HPNs. In some critical cases, the time slot of critical LPN is only occupied by HPNs if all other slots are reserved. The situation can arise when the priority weight of LPN is near the threshold of HPN.

Eq. 8 and Eq. 9 represent communication failure in PE-MAC and O-PEMAC respectively. To present a unified equation, to consolidate the communications failure probability of proposed schemes for cases where $(n-m)>m$, certain conditions are listed. The modified relation along with the case specific conditions is expressed in Eq. 10:

$$\begin{aligned} P\left(\mathcal{F}_P/\mathcal{F}_O|(n-m)>m\right) = \sum_{y=1}^{m}\left[\left(\binom{m}{y}q^y(1-q)^{m-y}\right)\left(\sum x = s^z\binom{z}{x}q^x(1-q)^{z-x}\right)\right] \\ given \begin{cases} s=1, z=y & \text{PE-MAC} \\ s=n-m-(y-1), z=n-m & \text{O-PEMAC} \end{cases} \end{aligned} \tag{10}$$

b: Case 2: (m>n-m i.e. HPNs > LPNs)

For cases where HPNs are greater than the LPNs, the possibility of failure in HPNs communication greatly increases. Failure in delivery of HPNs information to co-ordinator, hence, depends on the ratio of LPNs to HPNs. The probabillity of error in communication of HPNs in PE-MAC under such circumstances is presented in Eq. 11. Whereas, the failure in communication of HPNs (where HPNs > LPNs) in O-PEMAC is presented in Eq. 12.

$$\begin{aligned} P\left(\mathcal{F}_P|m>(n-m)\right) &= \frac{m!}{1!\,(m-1)!}q\,(1-q)^{m-1}\,(q) + \frac{m!}{2!\,(m-2)!}q^2\,(1-q)^{m-2} \times \left[\sum_{x=1}^{2}\binom{2}{x}q^x\,(1-q)^{2-x}\right] \\ &+ ... + \frac{m!}{(n-m)!\,(m-(n-m))!} \times q^{n-m}\,(1-q)^{m-(n-m)} \times \left[\sum_{x=1}^{n-m}\binom{n-m}{x}q^x(1-q)^{(n-m)-x}\right] \\ &+ \frac{m!}{(n-m+1)!\,(m-(n-m+1))!} \times q^{n-m+1} \times (1-q)^{m-(n-m+1)} + ... + \frac{m!}{(m)!\,(m-(m))!}q^m\,(1-q)^{m-(m)} \end{aligned} \tag{11}$$

$$\begin{aligned} P\left(\mathcal{F}_O|m>(n-m)\right) &= \frac{m!}{1!\,(m-1)!}q\,(1-q)^{m-1}\,(q)^{n-m} + \frac{m!}{2!\,(m-2)!}q^2\,(1-q)^{m-2} \times \\ &\left[\sum_{x=n-m-1}^{n-m}\binom{n-m}{x}q^x\,(1-q)^{n-m-x}\right] + ... + \frac{m!}{(n-m)!\,(m-(n-m))!}q^{n-m}\,(1-q)^{m-(n-m)} \times \\ &\left[\sum_{x=1}^{n-m}\binom{n-m}{x}q^x(1-q)^{n-m-x}\right] + \frac{m!}{(n-m+1)!\,(m-(n-m+1))!}q^{n-m+1}\,(1-q)^{m-(n-m+1)} + ...+ \\ &\frac{m!}{(m)!\,(m-(m))!}q^m\,(1-q)^{m-(m)} \end{aligned} \tag{12}$$

The probability of failure in communication of PE-MAC and O-PEMAC, Eq. 11 and Eq. 12, respectively can be expressed as a unified notation presented in Eq. 13. A detailed evaluation of the performance of the proposed schemes in comparison to the IEEE 802.15.4e is presented in Section IV.

$$\begin{aligned} P\left(\mathcal{F}_P/\mathcal{F}_O|m>(n-m)\right) &= \sum_{y=1}^{m}\left[\frac{\left(\binom{m}{y}q^y(1-q)^{m-y}\right)\left(\sum_{x=s}^{z}\binom{z}{x}q^x(1-q)^{z-x}\right)}{\left(\sum_{x=s}^{z}\binom{z}{x}q^x(1-q)^{z-x}\right)\left(u\left(y-(n-m)\right)\right)}\right] \\ given &\begin{cases} s=1,\ z=y & PE-MAC \\ s=n-m-(y-1),\ z=n-m & O-PEMAC \end{cases} \end{aligned} \tag{13}$$

3) Delay analysis for communications in HPNs for PE-MAC and O-PEMAC

In priority optimized MAC protocols, time constrained delivery of the information to the coordinator is very crucial. In case of PE-MAC, the retransmission allows improved average delay in communication from HPNs to the coordinator. The delay in communications from HPN to the coordinator is expressed in Eq. 14. In this equation, δ_p is the time taken from transmission initiation to the information delivery to the destination. It includes the transmitter and receiver processing dela and communications delay and is taken to be 600 μsec. T_{sf} is the duration of the superframe after which the next transmission takes place and ∂ is the delay to deliver ω percent of the entire traffic generated by an HPN. Eq. 15 represents the geometric series since geometric distribution is used to evaluate the delay of the communication originated from HPNs whereas Eq. 16 states the condition for evaluating P (for typical 802.15.4e network).

$$\partial = (P \times T_{sf} + \delta_p) \tag{14}$$

$$S_x = \sum_{x=0}^{i} a_x = \sum_{x=0}^{i} q^x = \frac{1-q^{i+1}}{1-q} \tag{15}$$

$$\forall (1-q) \times S_x > \omega, \ P = i \tag{16}$$

In this case the maximum delay, ∂_{max} is evaluated, within which ω percent of the traffic originated from the HPN is delivered to the destination. Here ω is set to 99.99% to meet the industrial standards and solving $(1-q) \times S_x > \omega$ for i i.e. $1 - q^{i+1} > \omega$ will give $i > \frac{|ln(1-w)|}{|ln(1-q)|}$
In order to define symmetric equation and to reduce the complexity, the number of HPNs in PE-MAC and O-PEMAC are limited to a maximum of 10 nodes. For O-PEMAC an approximate relation for maximum delay, ∂_{max} is used. The values of parameters P, for PE-MAC and O-PEMAC are defined by $i/2$ and $i/3$ respectively. Further discussion on the performance of PE-MAC and O-PEMAC in comparison to IEEE 802.15.4e LLDN and simulation results are presented in Section IV.

4) Quality Ensured Scheme (QES)

One of the primary requirements for close-loop control systems to establish effective control is the existence of predictable feedback link. Due to the unpredictable nature of wireless channels, the importance of deterministic behaviour further increases. A deterministic approach is introduced in QES to ensure the desired QoS for nodes communicating in a superframe. The proposed scheme offers a scheduled to shared slot ratio to offer 99.9% to 99.999% successful communication in a superframe depending on the requirements. The channel conditions for the previous transmissions are used to specify the desired scheduled to total slot ratio. Each superframe is divided in 'n' time slots for communication of information. A maximum of 'c' number of distinct nodes can communicate in a single superframe while '$n-c$' shared slots are added. Here 'c' is the number of nodes scheduled for communication in a particular frame.

Instead of contention based channel access in shared slots, as suggested in IEEE standards [9, 10], the presented model allows the coordinator (cluster head) to allocate the shared slots, in case a node's communication fails. To save the communication overhead and to allocate shared slots, group acknowledgement (G_{ACK}) is sent for an individual time frame. The bit sequence of G_{ACK} allows sensor nodes to identify which shared slot should they use to communicate if their communication was unsuccessful. The superframe structure and G_{ACK} bit sequence used in QES and PQES is presented in Figure 13. This allows sequential allotment (highest priority first) of shared slots to the nodes with unsuccessful communication. In case, a communication from a node remains unsuccessful after the retransmission or fails to get hold of a shared slot due to non-availability, the communication is rescheduled in the next superframe.
Total time slots (n) in a superframe are sum of the scheduled (c) and shared slots ($n-c$). The scheduled (c) to total slots (n) ratio is adjusted with each superframe using PRR from the previous communications which is modelled as a recursive function. A mathematical equation for the probability of failure in superframe communications is represented as follows.

$$P(Failure\ in\ superframe\ communication \mid c > (n-c)) = \sum_{y=1}^{n-c} \left[\left(\binom{c}{y} q^y (1-q)^{c-y} \right) \left(\sum_{x=(n-c)-(y-1)}^{n-c} \binom{n-c}{x} q^x \times (1-q)^{n-c-x} \right) \right] + \left[\sum_{y=n-c+1}^{c} \binom{c}{y} q^y (1-q)^{c-y} \right] \tag{17}$$

Note that q is the packet error rate and it represents the probability of failure in single packet communication. The QES ensures desired QoS by empirical estimation of the optimum ratio for the scheduled and total slots in a superframe as presented in Figure 14, where $P(Failure\ in\ superframe\ Communication) < 1 - D_Q$ is achieved for a given q. Here D_Q is the desired QoS bound for successful packet transmission rate.

5) Priority integrated Quality Ensured Scheme (PQES)

PQES offers a hybrid scheme which takes into consideration both priority weight function and QES to offer selective improvements in the communication of the nodes in IWSNs. PQES uses the dynamic priority system to identify the most critical nodes and ensures a pre-selected QoS for these nodes. Since PQES only focuses on improving the QoS for the critical nodes instead of optimizing the entire network communication, therefore the scheme allows a much better network load management and significantly optimizes the network efficiency. The mathematical model for PQES is also presented where the desired QoS in the high priority nodes is modelled as a negative binomial distribution and additional shared slots in a superframe are added accordingly to achieve the specified QoS. The mathematical formulation of PQES for added shared slots for desired success ratio of high priority nodes is modelled as follows:

$$S_n = w - (\psi \times n) \Big| \left[\sum_{x=\psi \times n}^{w} \binom{w-1}{x-1} q^x (1-q)^{m-x} > D_Q \right] \tag{18}$$

where $\psi \times n \le w \le n - \psi \times n$. Here S_n is the number of shared slots needed to achieve the desired QoS for $\psi \times n$ transmissions, where ψ is the percentage of total transmission slots with critical information which needs to be prioritized.
Performance evaluation of the proposed schemes, PE-MAC, O-PEMAC, QES and PQES, in comparison to IEEE 802.15.4e LLDN, is thoroughly covered in the following section.

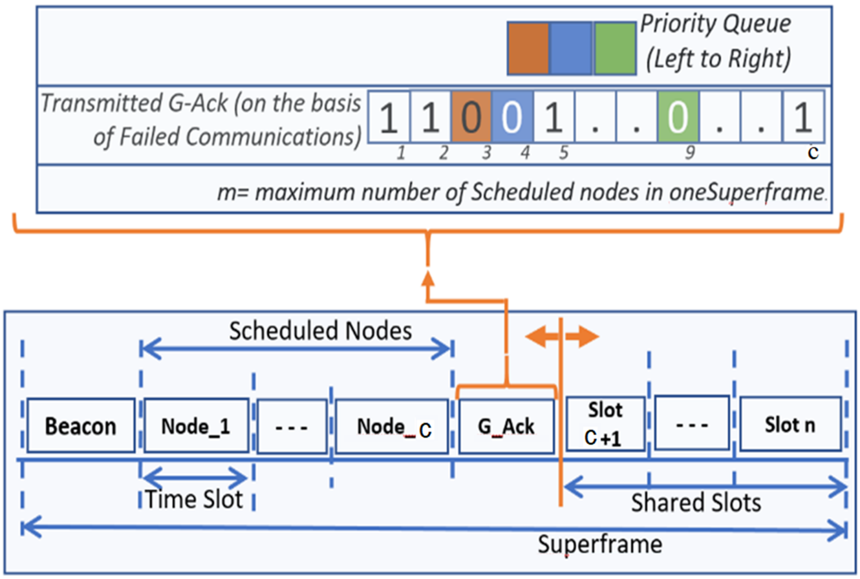


FIGURE 13: Superframe structure with c-Nodes

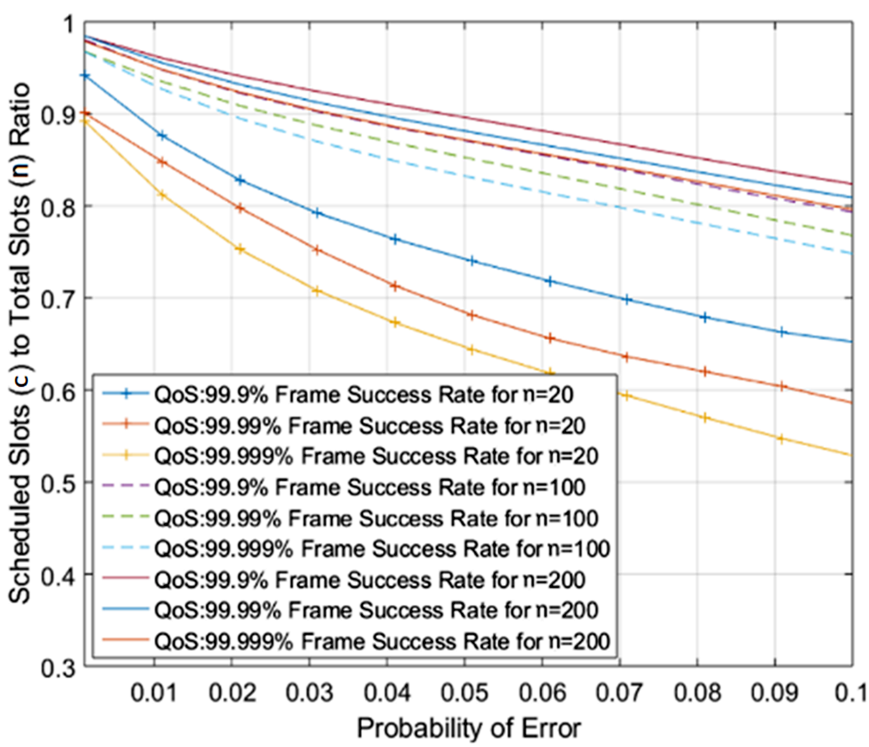


FIGURE 14: Scheduled slots to total slots ratio (Normalized) for desired QoS under different channel conditions

IV. RESULTS AND DISCUSSION

In this section the performance analysis of typical IEEE 802.15.4e LLDN along with the proposed schemes PE-MAC, O-PEMAC, QES and PQES is presented. The performance analysis of these protocols considers crucial performance metrics about reliability of communication and the overall delay.

A. RELIABILITY ANALYSIS IN HPNS' COMMUNICATION IN IEEE 802.15.4E

The IEEE 802.15.4e LLDN standard can incorporate up to 20 nodes within a single cluster and allows the coordinator to listen to the transmission within a duration of 10 milliseconds (ms), which is specified for a superframe in LLDN. The 10 ms superframe duration was particularly introduced for time critical industrial networks. Out of these 20 nodes, some may have precedence over the rest and due to critical nature of their information, need higher data delivery ratio compared to other nodes in the network. IEEE 802.15.4e itself do not include any precedence system and for that reason all the nodes are treated equally. For the performance evaluation in IEEE 802.15.4e, number of HPNs in a cluster is plotted against the percentage error in communication. The plots are presented in Figure 15 where the normalized frame error rate is plotted against the number of high priority nodes taking part in communications. Here, two parameters are defined: (1) the error rate in HPNs' communication (defined based on possible failures in communication of one or more HPNs) and (2) q (probability of failure in communication of any node in the network, independent of any other communication). Since IEEE 802.15.4e LLDN does not offer any error compensation for HPNs, the chances of frame error rate increase with the increase in number of HPNs.

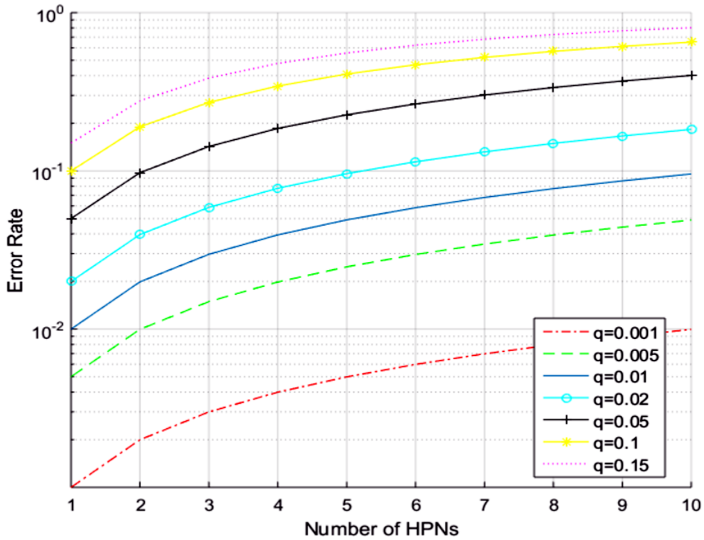


FIGURE 15: Error rate in communication of Typical IEEE 802.15.4e LLDN

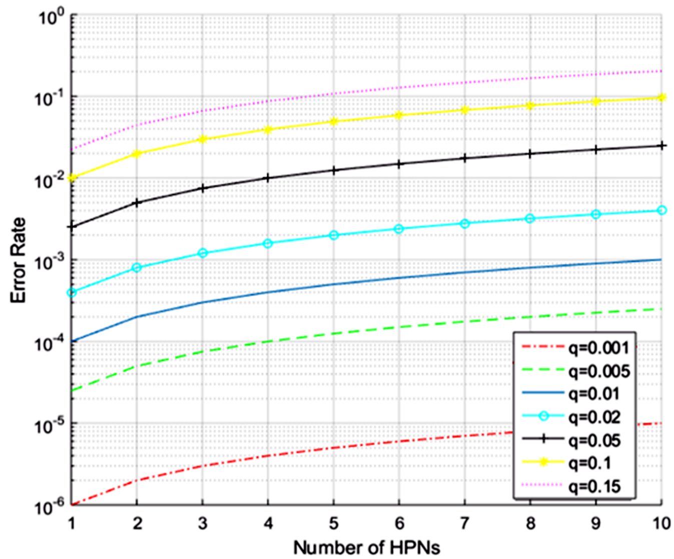


FIGURE 16: Error rate in superframe communication of PE-MAC

B. RELIABILITY IN COMMUNICATION OF HPNS' IN PE-MAC

The PE-MAC facilitates retransmission of failed communications of HPNs by reserving the time slots of the low priority traffic. Due to the same reason, the overall frame error rate in PE-MAC is notably less compared to IEEE 802.15.4e LLDN. The overall frame error rate for the PE-MAC is represented in Figure 16. Due to the adaptive change in the priority of the sensor nodes, effective information communication from the sensor nodes is also maintained which ensures timely delivery of data from important nodes without depriving specific LPNs. PE-MAC in comparison to IEEE 802.15.4e LLDN offers 75% error reduction in extreme cases whereas under normal circumstances. It is also observed that PE-MAC offers 99.999% successful frame reception in comparison to 99% achieved in IEEE 802.15.4e LLDN. Due to the short duration of superframe (10 ms), the significance of such improvement is very notable in regulatory and feedback control systems. Instead of 1 error frame every second (as in case of IEEE 802.15.4e), the proposed scheme offers 1 error frame per 17 minutes. This offers a notable improvement in stability of feedback systems and ensures the feedback requirements set forth by control and automation society.

C. RELIABILITY IN COMMUNICATION OF HPNS' IN O-PEMAC

The O-PEMAC aims to improve the communication reliability to facilitate critical and emergency communications in IWSNs. The allocation of additional bandwidth from low priority nodes and ability to transmit data belonging to critical nodes within the specified time

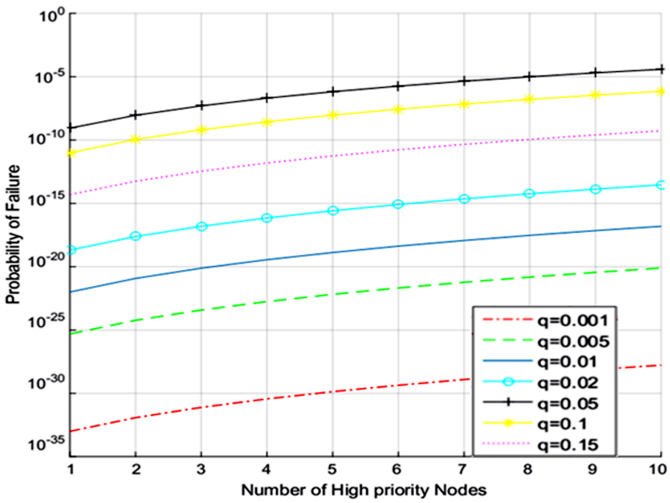


FIGURE 17: Superframe error rate in O-PEMAC

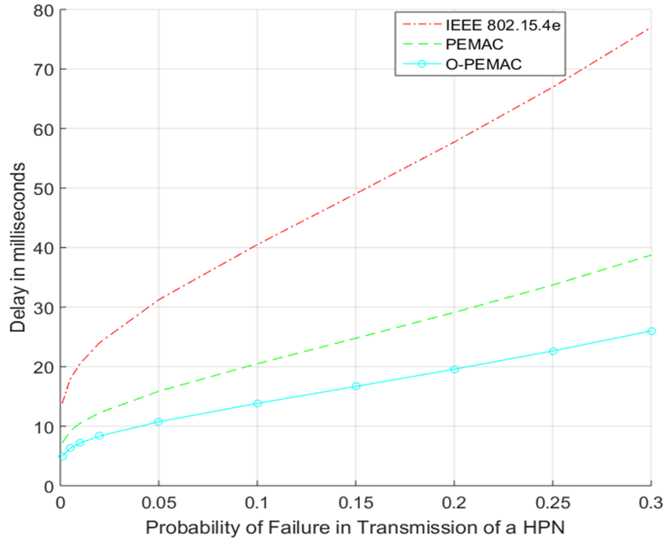


FIGURE 18: Maximum delay encountered in 99.99% traffic delivery to control system

window allows O-PEMAC to offer a very high communication reliability. The frame error rate for O-PEMAC is represented in Figure 17. O-PEMAC offers 99.999% successful frame rate for extreme channel conditions whereas, the reliability is further increased in less critical cases (up to 10^{-11} error rate for $q = 0.1$ and $m = 10$). The simulations show that even in the case of 10 HPNs ($m = 10$) scheduled per superframe and single transmission success rate as low as 85%, the scheme works reasonably well and reduces the chances of communication failure significantly (by ensuring 99.999%). This ensures suitability of O-PEMAC for emergency, regulatory and supervisory control applications in industries.

D. DELAY ANALYSIS FOR HPNS IN PE-MAC AND O-PEMAC

To evaluate the suitability of PE-MAC and O-PEMAC in real-time industrial applications, the maximum delay is investigated which ensures 99.99% packet success ratio for an individual node. The maximum delay for 99.99% successful packet reception is presented in Figure 18 for IEEE 802.15.4e LLDN, PE-MAC and O-PEMAC. The overall delay between two consecutive communications of an HPN are within tolerable bounds of process control for both PE-MAC and O-PEMAC. Even for the poor channel conditions (i.e., successful packet communication drops to 85%), the process control can effectively work with the integration of suitable control blocks like Smith predictor to establish a stable controlled environment in case of both PE-MAC and O-PEMAC.

E. PERFORMANCE ANALYSIS OF QES AND PQES

In this section, the results related to the evaluation of QES and PQES are divided into two parts. The first part discusses the overall impact of the proposed QES and presents an evaluation of reliability of the QES in comparison to the IEEE 802.15.4e LLDN. It also discusses the cost paid to ensure the desired QoS. In the second part, the overall network load optimization is analysed when the proposed dynamic priority system is embedded into the QES (PQES) in comparison to QES.

To maintain a desired rate of successful communication in a superframe, as a function of estimated PRR, an empirical form of scheduled slots (c) to total slots (n) ratio is represented in Figure 14. In this figure, a set of three curves is presented which evaluates the ratio of scheduled slots to total slots required to achieve the desired QoS of 99.9%, 99.99% or 99.999%. In addition to using three different values of QoS, the experiments also considers three discrete values of (n) (n=20,100 and 200). Note that the empirical curves in this figure suggest a ratio that will ensure the desired QoS for network communication. For evaluation purposes the ranges of p is used as 0.001 to 0.1. These parameter values are carefully chosen based on the channel conditions and requirements for successful communication in industrial environment. ($T_{deadline} - t$) is in a range between 10 milliseconds to 100 milliseconds depending on the size of the superframe. δ_1 and δ_2 (Eq. 4) are adjusted to 0.6 and 1/2.5 respectively to establish 60-40 contribution ratio based on time deadline and PRR.
The overall PRR for communication of QES and IEEE 802.15.4e LLDN are presented in Figure 19. It can be seen that the QES (following proposed $\frac{k}{n}$ ratio curves in Figure 14) notably improves the QoS compared to IEEE 802.15.4e as presented in Figure 19 (a). Figure 19 (b) shows the magnified view of the QES and it can be seen that in accordance with the curves provided in

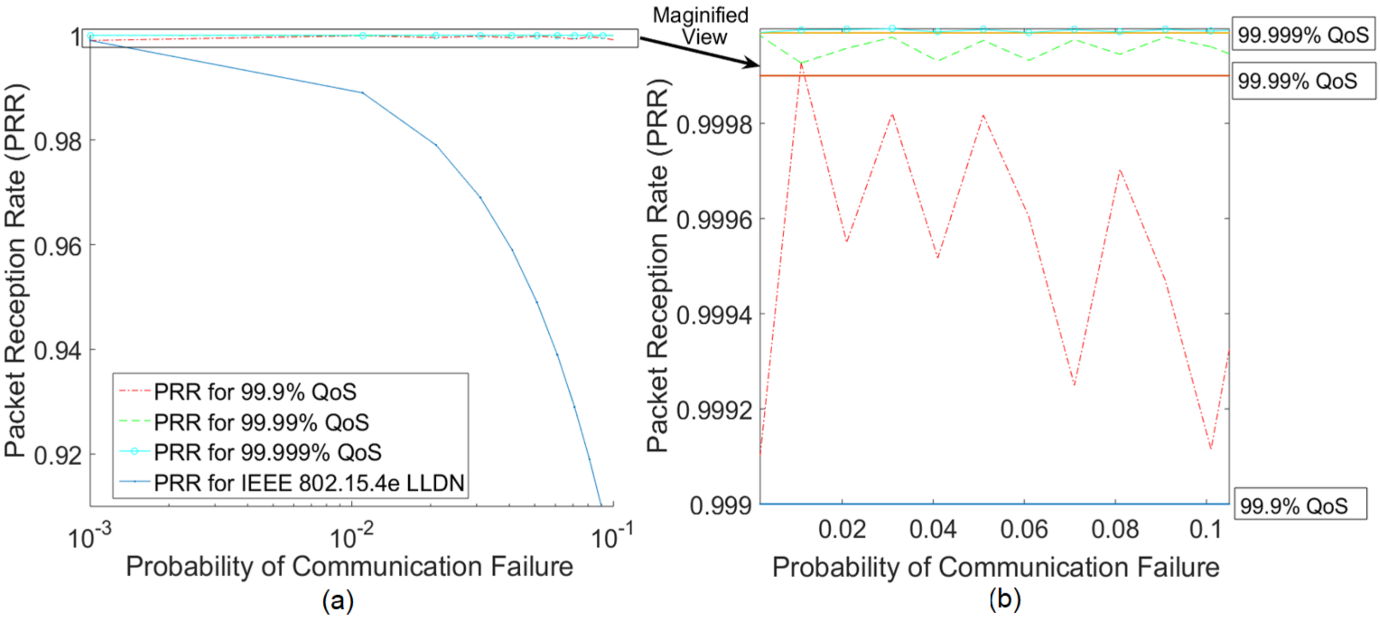


FIGURE 19: Packet Reception Rate (PRR): (a) PRR for the desired QoS cases in comparison to IEEE 802.15.4e LLDN; (b) Representation of the QoS aware communication: PRR in comparison to QoS bounds

Figure 19 (b), for all three of the presented cases, (99.9% QoS, 99.99% QoS and 99.999% QoS) the QoS threshold is not violated, ensuring higher QoS than the selected QoS threshold. However, the cost paid for improved QoS is represented in Figure 14 and Figure 20 (See red line with marker), where the number of scheduled slots are reduced notably to sustain desired QoS at poor channel conditions. It was also noted that for larger superframe sizes, the overall communication efficiency was improved under similar channel condition.

It is noted that the communication in IWSNs is only critical for selective nodes comprising 5% (or at max. 10% of total load). The implementation of proposed priority system allows to identify the high priority nodes, facilitating higher reliability for selected nodes' communication. The implementation of the priority system with 10% critical information content per superframe resulted in an increase of up to 20% additional load management capabilities of the network while maintaining the desired QoS. The percentage of the scheduled nodes for PQES in comparison to non-priority based QES is presented in Figure 20. In Figure 20, it can be observed that the network load management efficiency increases with the increase in the superframe size as evident from Figure 14 as well. Furthermore, it can also be deduced that the network load management ability suffers when higher reliability is desired. However, with the use of priority enabled reliability optimization, a notable increase in the network load management efficiency can be witnessed.

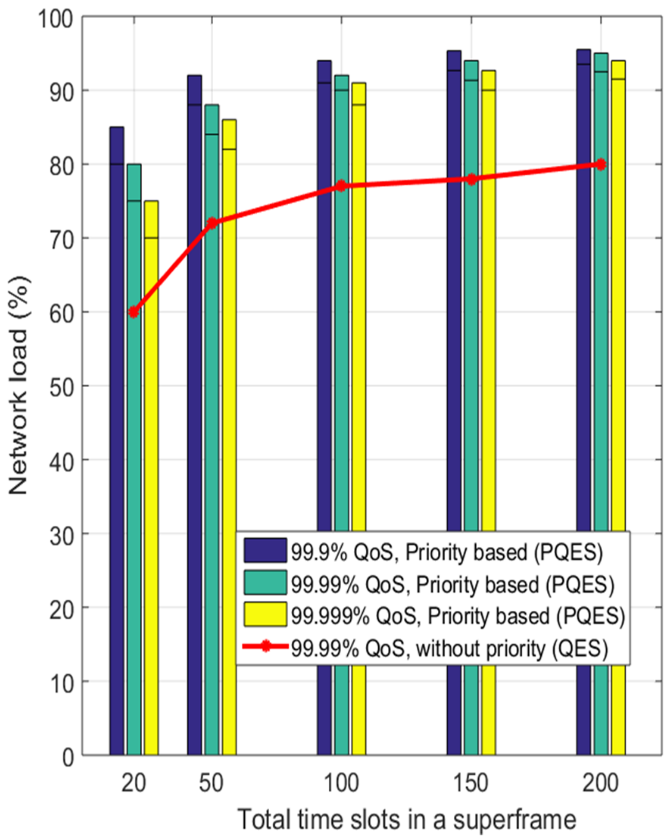


FIGURE 20: Maximum network load for achieving desired QoS with 10% critical information content per superframe

V. CONCLUSION AND FUTURE DIRECTIVES

This paper presents a dynamic priority based communication system for reliability and latency improvements in infrastructure-less networks, especially IWSNs. A dynamic priority system is proposed which classifies various communications taking place within the industrial environments. This classification helps in prioritizing the communication of critical nodes/data. To ensure real time and reliable communication, four MAC protocols were proposed and thoroughly evaluated.

PE-MAC and O-PEMAC offered an enhanced reliability and low latency for highly critical communications within the control and automation industry. These schemes implemented adaptive channel assignment to improve the communication of high priority nodes. Both the schemes offered notable improvements in the reliability and latency of HPNs communication in the network. It was observed that PE-MAC, in comparison to IEEE 802.15.4e LLDN, offered 75% reduction in error rate for critical cases. Whereas, O-PEMAC offered 99.999% successful frame reception rate for critical channel conditions. The reliability was further improved in less critical cases. With careful consideration of critical to non-critical nodes' ratio in each cluster, 99.99999% frame communication success rates can be achieved using O-PEMAC.

The paper also proposed QES and PQES protocols, which targeted the regulatory control applications requiring more deterministic reliability constraints. QES maintained up to 99.999% successful PRR under diverse channel conditions. Both QES and PQES adaptively adjust scheduled to shared slots ratio to offer a pre-specified PRR. In addition, PQES integrated the proposed priority system with QES to offer an improved network efficiency and load management.

The proposed work can be extended by incorporating asynchronous communication sources in the network. The proposed schemes can also be extended for multi-channel communications along with the introduction of adaptive and information centric security features.

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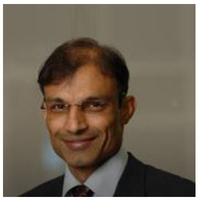

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